High Speed, High Current Monitoring System

by

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San Luis Obispo

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Abstract

Electronics testing requires lengthy data collection and analysis. Streamlining at least part of this process allows resource reallocation, and faster data processing. Verifying a signal's efficiency is key specification for a component's datasheet. This project focuses on streamlining data collection when measuring a device's output current. It combines amplifier design and digital interfacing to perform monitor a device's output current. A computer-enable interface displays a graphical output current representation. It ensures accurate, high speed, high current measurements while removing a person's need to manually plot data after testing. A new testing method provides room for company and product growth with eased data collection and analysis methods.

Key words: amplifier design, measurement, accuracy, analog-to-digital conversion, noise analysis

I. Introduction

This paper discusses the approach to creating an automated current detection and measurement system. Its implementation provides optimized electronics testing.

The project stems from my summer internship as a project manager at Wolfspeed, the sponsoring company. As a telecommunication company, they design, manufacture, and test multitudes of radio-frequency power transistor chips, ensuring their proper functioning and confirming their characteristics (gain, maximum power efficiency, frequency range) before shipping them to customers [1]. The current testing method includes an applications engineer connecting the drain and gate of the transistor to a power supply and manually adjusting the provided currents to verify specific parameters under different conditions while monitoring the output current [9]. The circuit input signal is a pulse with a 10 µs on-time and 90 µs off-time with varying frequencies associated with the on-time. The pulsed signal aims to reduce heat build-up which would harm the device. The engineer monitors the test, collecting the data in small increments. This lengthy process reduces the time available for data analysis, especially on a tight schedule.

Although the current system is the industry standard, streamlining at least a portion of the process could make a large difference in a product's design-to-market cycle. Hall-effect probes enable a user to sense the device under testing (DUT) circuit's signal through a magnetic field [9]. Such equipment is very sensitive and is only used in a well-ventilated and electro-static protected environment. I want to find an alternative to this process by focusing on the current-sensing aspect of power amplifier device testing. At this stage, this project cannot completely replace the current system as hall-effect probes are also used in load-pull testing [19].

This project's design conserves company resources by taking a step towards automating the data measurement and collection process. It requires understanding the multimeter design, which uses automated calibration techniques to optimize its measurement outputs [2][4]. The addition of a sensor and conversion circuit coupled with a single-board computer allows accurate data collection. A graphical user interface (GUI) displays collected data in graphical form [6]. Creating a new device enabling more efficient testing could revolutionize the electronics standard product timeline. By decreasing product testing cycles, companies increase their output and revenue. In the radio-frequency industry, companies such as Wolfspeed can become greater players in a market that is currently dominated by 11 corporations [7].

II. Customer Needs, Requirements and Specifications

Chapter II relays customer needs as well as project requirements and specifications. Their outlines, further explained below, provide a basis for the design process. My limited power transistor testing knowledge makes the visualization of my final product difficult.

Customer Needs Assessment

Phone calls with company representatives (Wolfspeed), including Richard Wilson, reveal the following customer needs. The device fits on a lab testing bench to perform high speed and high current measurements. The system facilitates effective data acquisition while requiring minimal engineer intervention. The graphical user interface optimizes data analysis through graphical signal displays. The requirements and specifications (Table 1) summarizes these needs. Testing the device's compatibility with high power cannot occur at Cal Poly due to limited equipment. A solution involves lowering the input signal's voltage, thus reducing the device's output power.

Requirements and Specifications

Market analysis and discussions with the sponsoring company (Wolfspeed) have yielded the Table 1 requirements and specifications [7]. Other specifications rely on previous designs and needs expressed in the customer needs assessment.

Marketing Requirements	Engineering Specifications	Justification
4	The system's current measurement ranges between 0.1 A and 30 A with a 1% tolerance.	The measurements require varying input drain-bias currents.
5	The system plots output current (A) vs. time (ms).	The device displays the data clearly, enabling further analysis.
3	The enclosure provides a ground plane, protecting the user and device from the high device current.	High power devices cause electrocution risks.
4	The system automatically calibrates (auto-ranges) its measurement system, remaining accurate between 0.1 A and 30 A.	Input current (0.1 A – 30 A) requires accurate reporting.
5	Graphical user interface (GUI) displays output current (A) vs. time (ms).	The GUI relays system readings.
2	Maximum dimensions: 8" x 8" x 4".	Fits on a lab bench among other equipment.
1	Production cost does not exceed $1,000.	Based upon competitive market analysis [7].
Marketing Requirements 1. Low cost relative to currently available systems 2. Compact 3. High output current 4. Accurate current measurements 5. Graphical data display		

TABLE 1: REQUIREMENTS AND SPECIFICATIONS

The requirements and specifications table format derives from [10], Chapter 3.

III. Functional Decomposition

Chapter III provides the project's functional decomposition in varying detail. Figure 1 depicts a system overview. The function generator, power supply, microprocessor, and monitor require purchasing rather than design. Most of the design revolves around component interfacing. Ideally, components can be downsized and confined to a small box, providing easy set-up for the engineer. The tested device is provided by the company, thus eliminating any related design work.
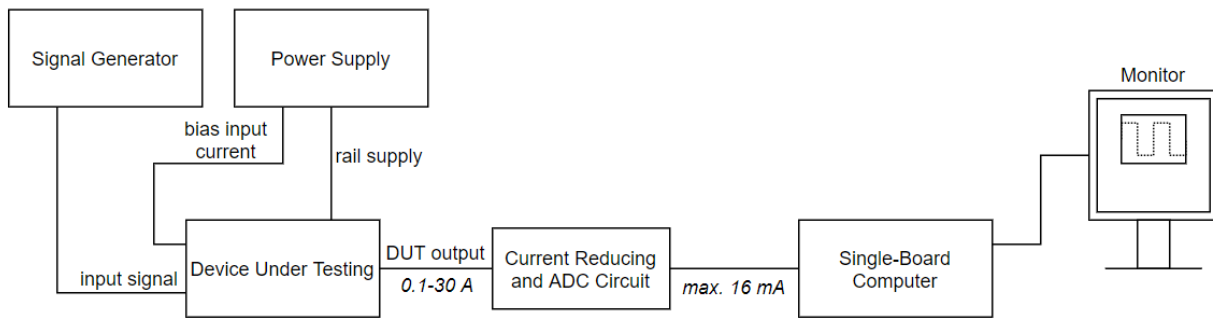
FIGURE 1: SYSTEM OVERVIEW

Level 0

A level 0 block diagram (Figure 2) provides an overview of the whole system's inputs and outputs. The functionality description (Table 2) further describes the device module and its required inputs and outputs.
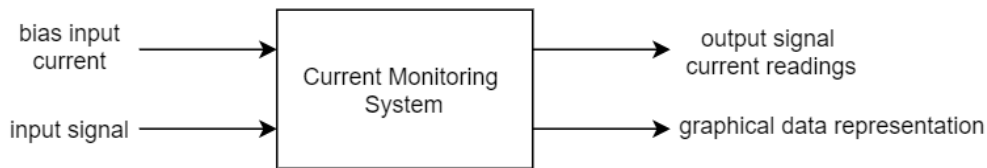
FIGURE 2: LEVEL 0 FUNCTIONALITY

Module	Current monitoring system
Inputs	- bias input current: between 0.1 A and 30 A. - input signal: continuous wave pulse using a 10% duty cycle.
Outputs	- output current readings: between 0.1 A and 30 A. - graphical data representation: input and output currents vs. time.
Functionality	Performs measurements of a radio-frequency power transistor output current signal output.

TABLE 2: LEVEL 0 FUNCTIONALITY

Level 1

Figure 3 depicts a level 1 block diagram of the device. It illustrates the board's connection with the device. Table 3 describes the modules' inputs and outputs, including their functionalities. The single-board computer is key to the device success as it computes the output data analysis [2][3]. The board's accuracy can be tested by connecting a light-emitting diode (LED) to a device pin and measuring the current supplied to the LED.

FIGURE 3: LEVEL 1 FUNCTIONALITY

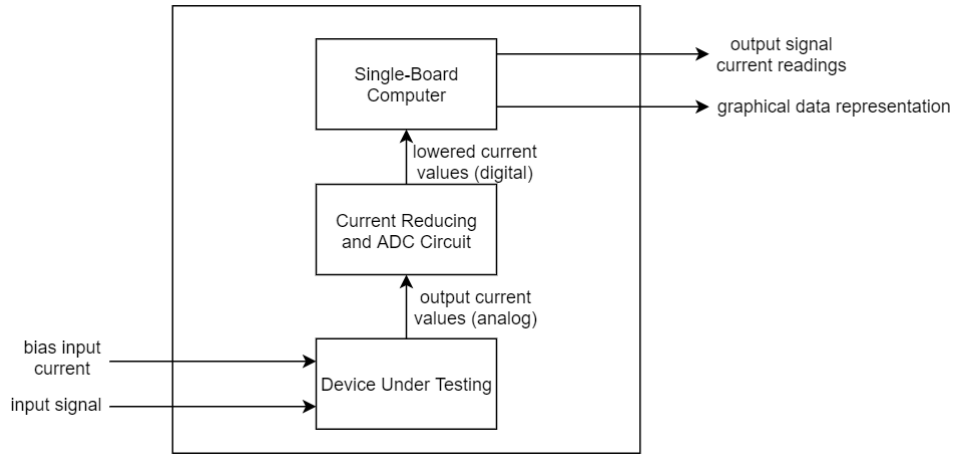| Module 1	Device under testing
Inputs (Module 1)	- bias input current: between 0.1 A and 30 A. - input signal: continuous wave pulse using a 10% duty cycle.
Outputs (Module 1)	- output current values (analog): analog signal output current.
Functionality (Module 1)	Performs measurements of a radio-frequency power transistor current output and efficiency, producing valuable data to the microprocessor.
Module 2	Current Reducing and ADC Circuit
Inputs (Module 2)	- output current (analog): analog signal output current
Outputs (Module 2)	- lowered output current (digital): digitized signal output current, reduced to 16 mA peak-to-peak.
Functionality (Module 2)	Reduces the DUT's output current peaks to avoid burning the board while digitizing the signal so the board can process the data.
Module 3	Single-board computer
Inputs (Module 3)	- processed output current values
Outputs (Module 3)	- output signal current readings: between 0.1 A and 30 A. - graphical representation: input and output currents vs. time.
Functionality (Module 3)	The testing set-up's output provides the data needed by the microprocessor to produce a graphical representation of the device's power efficiency.

TABLE 3: LEVEL 1 FUNCTIONALITY

The meticulous work required to successfully create this device drives a rigorous timeline and creates costs further described in Chapter IV.

IV. Project Planning

The project design course set forth the project planning elements. The dates and expectations rely on information from the project sponsor, the advisor, as well as the university's electrical engineering department senior project guidelines. Table 4 denotes the project deliverables and their associated completion dates. These dates remain tentative and subject to change. Due to the COVID-19 pandemic, the timeline and deliverables have drastically changed. Without access to a laboratory, this project has become simulation and software based, removing the need for physical protypes.

Delivery Date	Deliverable Description
12/09/2019	Project Plan
01/17/2020	Updated Project Schedule
01/27/2020	Design Review
03/13/2020	EE 461 Report
~~4/01/2020~~	~~Design Prototype~~
04/20/2020	Revised Report
05/10/2020	Revised GUI Program
05/28/2020	EE 462 Demo
05/25/2020	Updated ABET Sr. Project Analysis
~~6/02/2020~~	~~Senior Project Expo Poster~~
06/12/2020	EE 462 Report

TABLE 4: DELIVERABLES

Project Timeline

This quarter's timeline provides the basis for all subsequent dates. Combining optimistic and pessimistic expectations produces the following figures 4, 5, and 6, subject to change as the project progresses. Accounting for three design phases, the project timeline extends across many months to bring this project to fruition. I intend to finish all technical activities by Spring Quarter, week 7 per Figure 6. Appendix B includes an up-to-date project timeline.
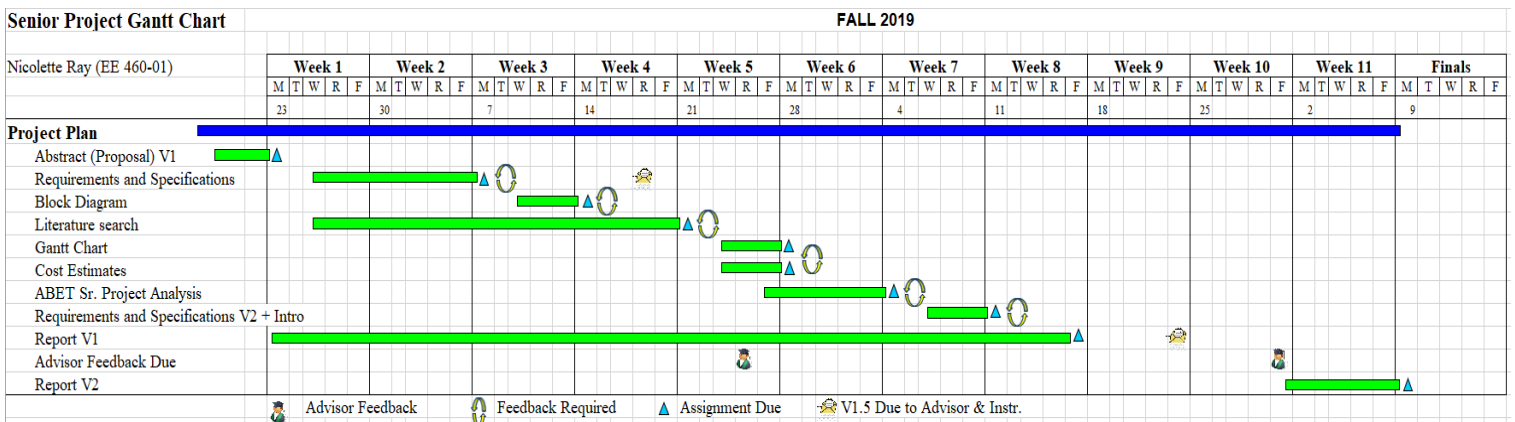

FIGURE 4: FALL 2020 GANTT CHART

Senior Project Gantt Chart WINTER 2020

Nicolette Ray (EE 460-01)

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Finals

Project Design
- Problem Identification
- Initial Design
- Update Design Documents
- Simulation and Analysis
- Parts Ordering + Shipping
- GUI Programming
- Prototype
- Test
- Re-design
- Parts Ordering + Shipping
- Prototype
- Test
- Re-design (if needed)
- Report V3
- Advisor Feedback Due

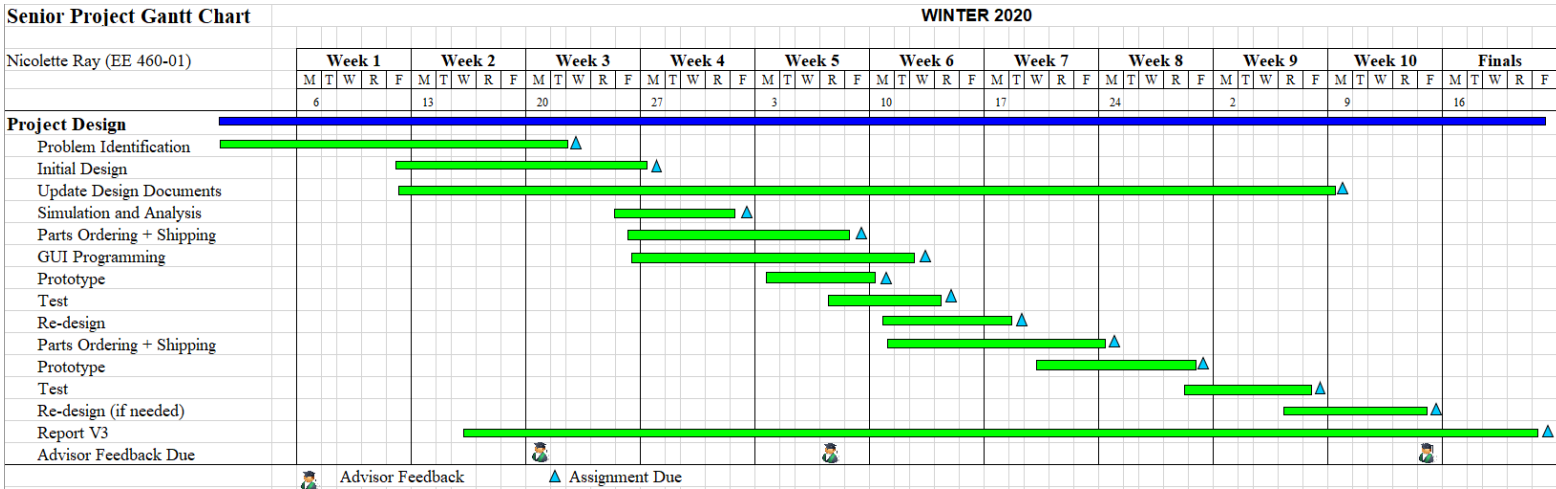Advisor Feedback   △ Assignment Due

FIGURE 5: WINTER 2020 GANTT CHART

Extended Task Descriptions:
- Problem Identification: narrowing the main focus and design requirements of the project (sponsor meeting)
- Initial Design: code outline and comments, narrowing of power instruments used in testing set-up
- Update Design documents: ensuring that every step is documented for future reference
- Simulation and Analysis: run LTSpice or AWR simulations and analyze results to make appropriate design changes.
- Parts Ordering & Shipping: sending sponsor list of required equipment/components and having them sent to San Luis Obispo
- GUI Programming: graphical user interface creation

Senior Project Gantt Chart SPRING 2020

Nicolette Ray (EE 460-01)

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Finals

Continuation of Project
- Re-design (if applicable)
- Parts Ordering + Shipping
- Prototype
- Test
- Finalize Design + Parts List
- Build Final Version of Device
- Final Device Testing
- Report V3.5
- Report V4
- Advisor Feedback Due

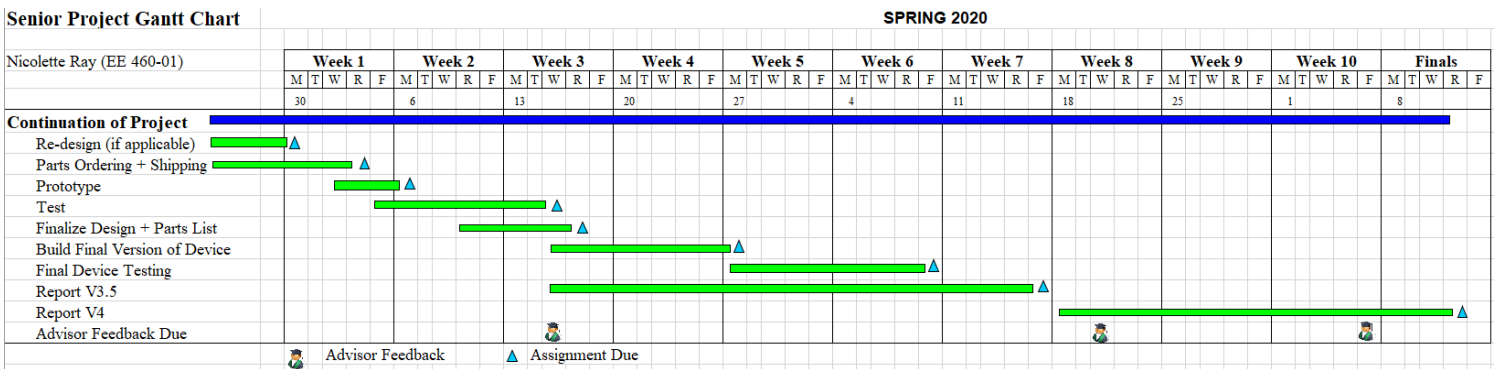Advisor Feedback   △ Assignment Due

FIGURE 6: SPRING 2020 GANTT CHART

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Cost Estimates

Table 5 describes the project's cost estimation. These numbers are subject to change as I narrow the project design. Extended calculation equations are not included.

Expense Category	Unit Cost	Quantity	Extended Cost	Justification
Student Labor	$50 per hour	180 hours	$9,000	I consider my labor worth approximately $50/hr based on past internship compensation.
Company Resources (consulting)	$60 per hour	20	$1,200	The project sponsor provides guidance throughout the project development.
Multimeter (model TBD)	$200	1	$200	Fluke multimeter costs often exceed $200.
Raspberry Pi 4	$35	1	$35	The Raspberry Pi 4
Miscellaneous components	$0.70	50	$35	Miscellaneous components (resistors, wires, etc.) cost approximately $0.50, I expect variations.
Travels (Wolfspeed campus, Morgan Hill, CA)	$33 per trip	3 trips	$99	$0.20 per gallon for a 165-mile trip.
Total Cost				$10, 564 -> $11,000 (over-estimate)

TABLE 5: COST ESTIMATES

The sponsoring company agreed to reimburse project expenses up to $15,000 which remain within the anticipated project cost range. Table 6, in Appendix B, discusses the actual project costs upon completion. Component costs were higher than anticipated and additional equipment needed to be purchased. The COVD-19 pandemic shifted academics to a work-from-home basis. As such, I did not have a proper laboratory set-up and bought specific supplies as a remedy, including a multimeter.

V. Resistor-Amplifier Circuit Design

Chapter V discusses the current sensing, and data conversion circuit development stages. The different circuit components' interactions with each other entail further analysis, including but not limited to selecting an appropriate sensor, amplifier device, and verifying signal-to-noise ratios.

Detecting the signal accurately and reliably requires additional components and design work. Hall-effect sensors were considered but do not provide adequate bandwidth for monitoring a device at a high frequency, 1 to 10 MHz. Several approaches have been considered: a simple operational amplifier paired with appropriately chosen resistors to control signal gain, or an instrumentation amplifier with a single gain-controlling resistor. An open-collector amplifier, such as the BU7251, was ruled out due to its slow low-to-high transition rate [20]. The instrumentation amplifier's internal buffer amplifiers provide high input impedance and reliable outputs, making it most suitable for this project [12].
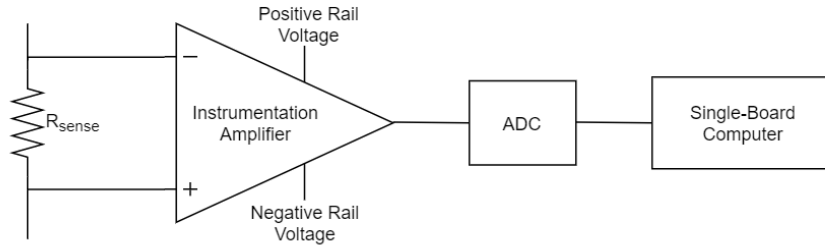

FIGURE 7: SIGNAL DETECTION AND CONVERSION DIAGRAM

Final decisions regarding component selection are further discussed in the following sections.

Current Sense Resistor

Obtaining a current reading, requires placing a resistor, R_{sense}, in series with the DUT. Because the signal's current can fluctuate between 0.1 A and 30 A, the resistor choice affects whether the amplifier can detect the signal and amplify it enough for ADC detection and handling. This value can be controlled with a low enough resistance using equation 1.

$$V = I \times R \tag{1}$$

Using a 1 mΩ resistor as R_{sense}, the measured voltage could be as low as 100 µV and as high as 30 mV. While the higher resistor voltage could be detected by the amplifier, the lower end value may be missed due to device noise. Further noise analysis involving the resistor, amplifier circuit, and ADC provides important insight for this choice and is discussed in "Circuit Noise Analysis." After investigating both extreme cases (case 1: 0.1 A, case 2: 30 A), the optimal resistor value for case 1 is 71.5 mΩ, creating a 7.15 mV voltage drop, while its value for case 2 is 1 mΩ, with a 30 mV voltage drop.

$$Resistor\ Noise \approx (4nV) \times \sqrt{(resistor\ value\ in\ k\Omega)} \tag{2}$$

Using equation (2), provided in the AD8421 datasheet, the resistor, R_{sense}, noise is calculated as 0.004 nV/√Hz when equal to 1 mΩ and 0.034 nV/√Hz when equal to 71.5 mΩ [16].

Amplifier Selection

Selecting an instrumentation amplifier requires several considerations: optimal bandwidth, slew rates, nominal gain values, input noise. Understanding operational amplifier noise models helped me decide, when reading different devices' datasheets, which ones would be most appropriate for this project [13][14]. I settled on the AD8295 for 1 MHz applications, and the AD8421 for 10 MHz ones [15][16]. Both components have an adjustable gain via an external resistor. I picked a gain of 100. In the next two subsections, I will discuss the appeal of each component.

AD8295

A useful feature of the AD8295 package is that it includes two other operational amplifiers which could be used as buffers if the reference pin were utilized [15]. It is optimal for 1 MHz applications. Table 9 of the device datasheet states that a 499 Ω resistor, R_G, yields the desired gain value. The voltage noise and current noise of the instrumentation amplifier (IA) are calculated through the equations below, (3) and (4) [16].

$$Voltage\ Noise\ of\ IA = \sqrt{\left(\left(\frac{Output\ Noise}{Gain}\right)^2 + (Input\ Noise)^2 + (Noise\ of\ R_G\ Resistor)^2\right)} \qquad (3)$$

This calculation yields a voltage noise of 8.51 nV/√Hz regardless of the sensor resistance. Equation (4) refers to 'Source Resistance Value' which, in this circuit, corresponds to R_{sense}. The instrumentation amplifier's current noise is 4_E^{-8} nV/√Hz when R_{sense} is 1 mΩ and 2.86_E^{-6} nV/√Hz when it is 71.5 mΩ.

$$Current\ Noise\ of\ IA = \sqrt{((Source\ Resistance\ Value) \times (Specified\ Current\ Noise))^2} \qquad (4)$$

$$Total\ Noise\ Density = \sqrt{((Resistor\ Noise)^2 + (Voltage\ Noise\ of\ IA)^2 + (Current\ Noise\ of\ IA)^2)} \qquad (5)$$

In equation (5), 'Resistor Noise' corresponds to the noise due to R_{sense}, calculated in the previous section as: 0.004 nV/√Hz when equal to 1 mΩ and 0.034 nV/√Hz when equal to 71.5 mΩ. The calculation determines the total noise density of the instrumentation amplifier, referred to input, as approximately 8.51 nV/√Hz regardless of the chosen current sense resistor [16]. This value is equivalent to 8.51 μV root-mean-squared (RMS).

AD8421

The AD8421 is optimized for a high gain at 10 MHz and its datasheet discusses its capability of "driving an ADC in a data acquisition system" [16]. Its gain is set to 100 using a 100 Ω resistor. The noise of its input stage is determined using equations (2), (3), (4), and (5). The instrumentation amplifier's voltage noise is 3.5 nV/√Hz regardless of the sensor resistance value. The device's current noise is 2_E^{-7} nV/√Hz when R_{sense} is 1 mΩ and 1.43_E^{-5} nV/√Hz when it is 71.5 mΩ. The input noise due to R_{sense} remains the same as for the AD8295 case above: 0.004 nV/√Hz when equal to 1 mΩ and 0.034 nV/√Hz when equal to 71.5 mΩ as calculated in "Resistor Sense

Selection." Equation (5) determines the total noise density of the instrumentation amplifier, referred to input, as approximately 3.5 nV/√Hz regardless of the chosen sensor resistance. Its RMS equivalent is approximately 4.95 µV.

ADC

The Raspberry Pi 4 only accepts digital inputs, which is why an analog-to-digital converter is added between the amplifier circuit and the single-board computer. The ADS1115 is a 16-bit converter, accepting input analog voltage between 0 V and 3.3 V – its source voltage [17]. The expected device performance under ideal conditions is determined through equation (6), where N represents the number of bits [11].

$$SNR = 6.02N + 1.76dB \tag{6}$$

Thus, the ADC's performance, or signal-to-noise ratio, will be 98.08dB, maximum. However, in practice it is unlikely that such a performance can be achieved. The device's highest data rate is 860 samples per second, creating a maximum 8.75 µV input noise. This value is further utilized in "Circuit Noise Analysis."

Circuit Noise Analysis

Circuit noise analysis provides insight into a circuit's behavior. If the signal-to-noise ratio is too low, the circuit becomes unreliable and thus non-relevant accurate and precise measurement applications. Previously, in "Amplifier Selection," the devices' noise referred to the input were calculated. The lowest input into the instrumentation amplifier is 7.15 mV, much larger than each device's input noise, meaning that this design remains feasible. Further analysis involves focusing on the circuit's output going into the ADC to ensure accurate measurements. This is done using LTSpice simulations.

AD8295

LTSpice does not contain an exact model of the AD8295, but the instrumentation amplifier can be implemented with the AD8222 model as shown in Figure 8. I set rail voltages to +/- 15 V and emulated the DUT circuit through a current source to supply the current sense resistor. Figure 8 contains the circuit schematic with a 1 mΩ resistor. The output noise of the circuit is not affected by R$_{sense}$'s value, making a circuit with a 71.5 mΩ resistor irrelevant.
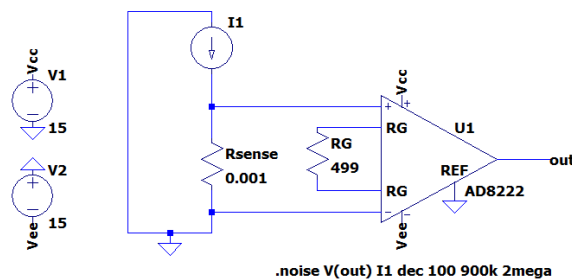

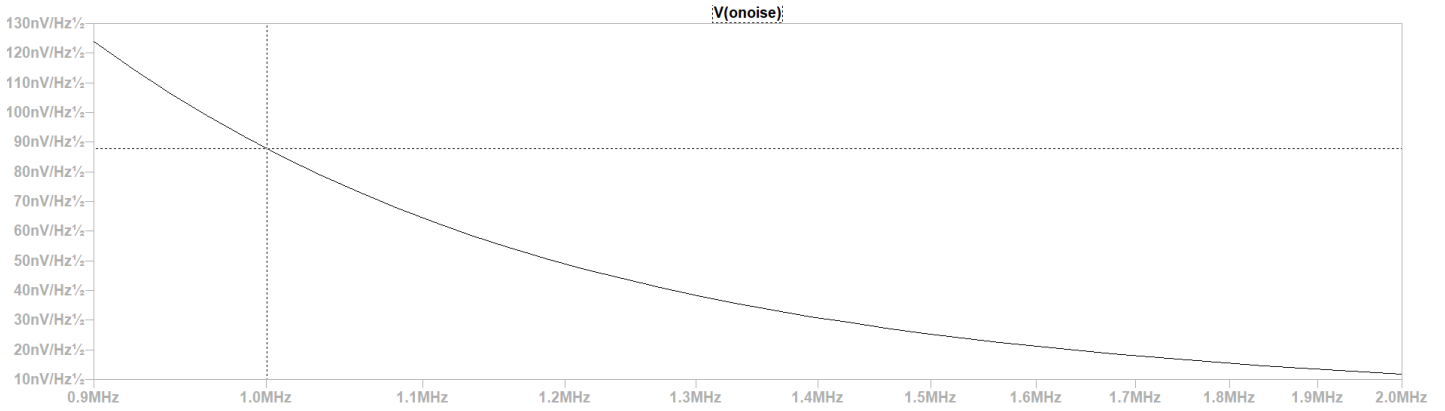FIGURE 8: SCHEMATIC FOR 1 MHZ CIRCUIT DESIGN (AD8222 ACTING AS AD8295)

FIGURE 9: OUTPUT VOLTAGE NOISE VS. FREQUENCY (AD822 ACTING AS AD8295)

Figure 9 demonstrates the operational amplifier circuit's output noise as 1 MHz reaches approximately 87.815 nV/√Hz which is equivalent to 87.815 µV. Total noise calculations use equation (5) to combine the op-amp output noise and the ADC input noise, yielding a total noise, referred to the ADC input, of 88.250 µV. Next, the signal-to-noise ratio (SNR) is evaluated using equation (6) [14].

$$SNR = 20log_{10}(\frac{V_{i(rms)}}{E_{ni}}) \tag{6}$$

$V_{i(rms)}$ refers to the op-amp circuit output, which is 0.715 V in case 1 (0.1 A, R_{sense} is 71.5 mΩ), and 3 V in case 2 (0.1 A, R_{sense} is 1 mΩ). E_{ni} refers to the total noise, referred to the ADC input, 88.250 µV. Using these values in the equation, the circuit's SNR is approximately 78.172 dB in case 1, and 90.628 dB in case 2. Both values are greater than 41 dB, validating this design.

AD8421

The AD8421 model is available within the software, facilitating simulations.
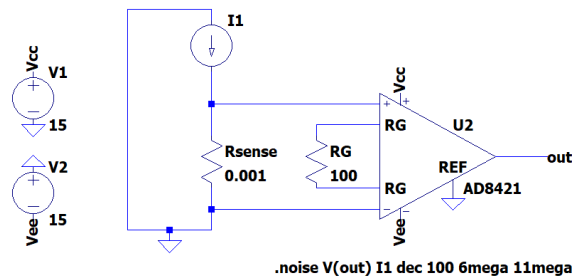

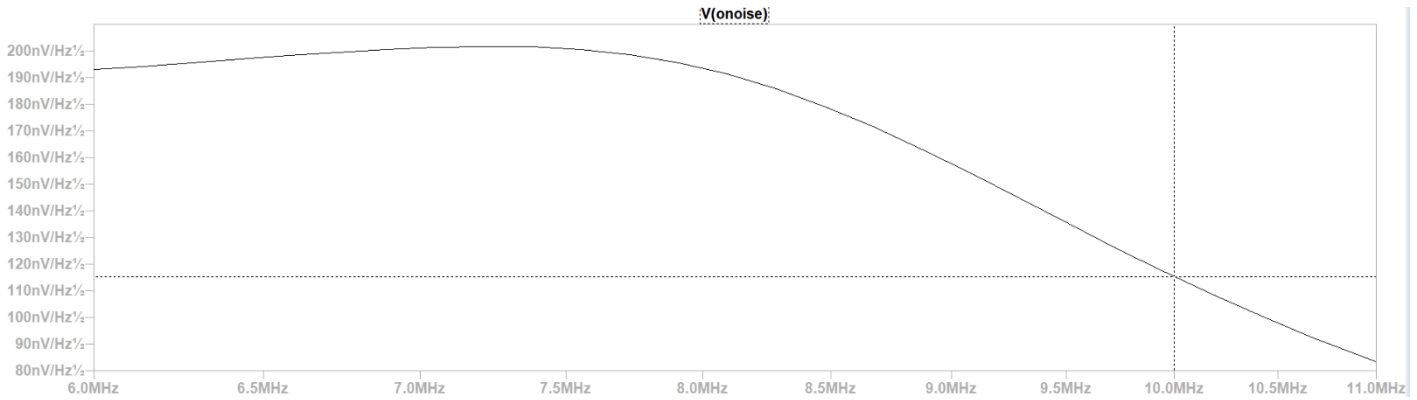FIGURE 10: SCHEMATIC FOR 10 MHZ CIRCUIT DESIGN (AD8421)

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:V(onoise)

FIGURE 11: OUTPUT VOLTAGE NOISE VS. FREQUENCY (AD8421)

Figure 11 shows a LTSpice-generated graph representing the output voltage noise due to the op-amp circuit in Figure 10. The operational amplifier circuit's output noise at 10 MHz reaches approximately 114.147 nV/√Hz which is equivalent to 360.996 µV. Like in the AD8295 case, the total noise calculations rely on equation (5). They determine the total noise, referred to the ADC input, as 361.102 µV. Using equation (6), the circuit's output SNR is approximately 65.934 dB in case 1, and 78.390 dB in case 2. Both values are greater than 41 dB, validating this design.

Prototype

Testing without laboratory access creates obstacles when validating a circuit design. I have created a prototype for a 10 MHz input signal, shown in Figure 8, using double-sided copper boards, super glue, copper wire, a breakout board, a soldering iron, and appropriate components [18]. The photograph in Figure 12a contains two copper boards, one for each chosen resistor value (1 mΩ and 71.5 mΩ). Their layouts are identical. The base copper board serves as universal ground, labeled as "GND." Copper wire ensures minimal resistance between components which is crucial when dealing with such small voltage values, determined in "Current Sense Resistor." R_{sense} is not grounded because in practice it would be connect in series with the DUT circuit. Battery clips are connected at the top and bottom of the board, at the "GND" and "+Vs" / "-Vs" labels, to power the instrumentation amplifier, AD8421, which is connected via the breakout board on the right [16]. Capacitors are connected to the "+Vs" and "-Vs" copper islands to bypass any potential alternative-current (AC) signal from the source. Figure 12b focus on the circuit board containing the 71.5 mΩ resistor. The orange jumper wire connected to a lead on the breakout board conducts the output of the instrumentation amplifier to the ADC.
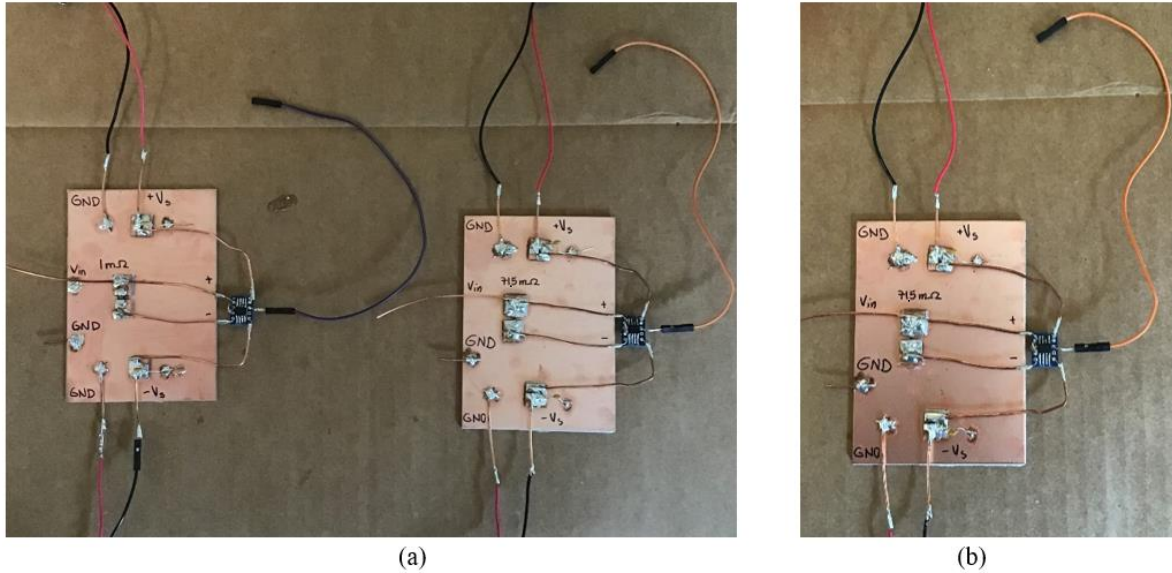
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FIGURE 12: CIRCUIT PROTOTYPE

Continuity checks verified correct connections between wires, components, and copper islands. I performed a DC test by first connecting the lower-most R_{sense} lead to the ground plane and plugging in 9 V batteries to power the op-amp rails. Then, I connected a AAA battery, nominal voltage 1.5 V and actual voltage of 1.45 V, to 'V$_{in}$' and 'GND' and measured the op-amp output. Because its output cannot be greater than the rail-voltage, the device's actual gain could not be verified since a 1.5 V input implies a 150 V output. This test's output showed a 6.5 V output, lower than expected. This may be due to the unusual testing set-up, needing to hold leads directly to the power source, or the batteries draining voltage too quickly. Please note that I ran the simulations with a +/- 15 V rail voltage, different from how I was able to test it. I do not have access to a signal generator, preventing further testing.

VI. Data Processing and Graphical User Interface Development

Although the original project scope involved users setting testing parameters via the graphical user interface (GUI), its narrowed revision focuses on plotting current readings. This process involves saving detected information in a comma-separated values file (.csv) and parsing through it to create a plot of voltage values. These values correspond to the voltage drop across R_{sense} and thus represent the DUT's output current. To accurately read such information, the Raspberry Pi must interface with the ADC. This is enabled by CircuitPython which already includes libraries for the ADS1115 [5]. The two devices communicate using the I2C protocol, decreasing the amount of necessary wiring as only 4 pins are used on each component: GND, SCL, SDA, and VDD or 3.3V on the ADS1115 and Raspberry Pi 4 respectively.

Appendix A includes the code used for this project. It includes segments to collect data from the ADC and store its values as well as timestamps as distinct lists. These objects are then saved as a comma-separated values (csv) file titled 'TestRun.csv.' The code offers two ways of processing data: directly from the run file or parsing through a pre-saved csv file. Ultimately, the data is plotted to display the output signal vs. time in a separate window, seen in Figure 13. This GUI was created using Python's built-in 'tkinter' library. Because I could not collect actual testing data, I selected data values to create an example graph. I chose 'x' markers and linear behavior to demonstrate how it could look. The axes labels are pre-determined. Their range and scale adjust depending on the dataset.
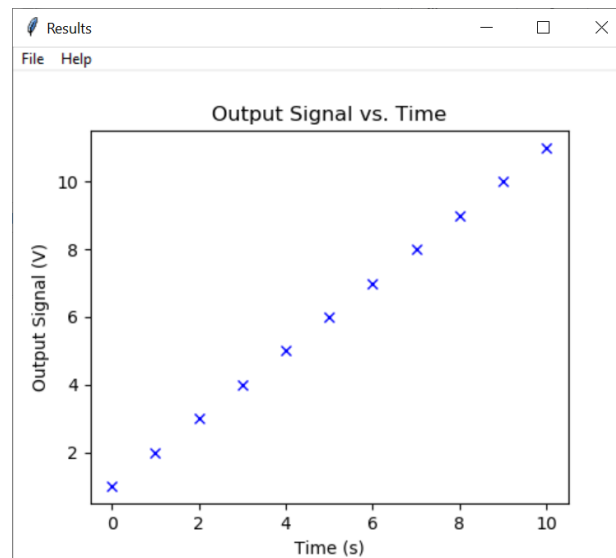
FIGURE 13: MAIN WINDOW (GUI)

This separate window, titled 'Results,' includes a menu bar. This offers the user several choices upon seeing the test results. Figures 14 and 15 exhibit how clicking on a menu bar's elements reveals a drop-down menu with one or two further options. The 'Help' element reveals an 'About' option which shares a program description, including my name, as the programmer, and the year of its creation as shown in Figure 14b.

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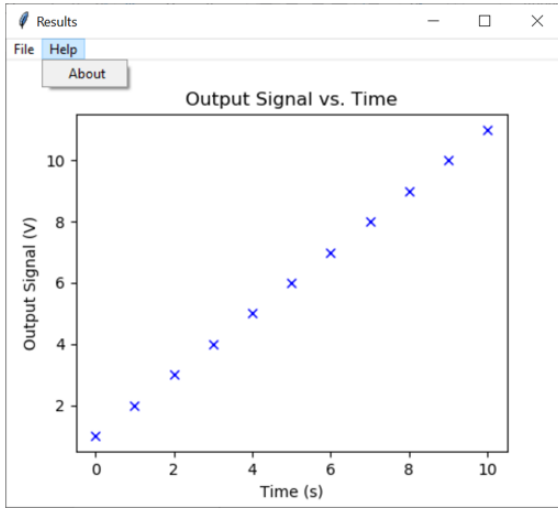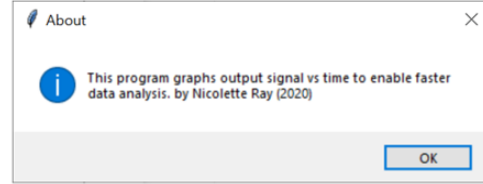
(a)   (b)

FIGURE 14: MAIN WINDOW MENU BAR - ABOUT (GUI)

On the left of the menu bar, clicking on 'File' offers the user two options: 'Saved Data' and 'Quit Program.' Because the program automatically edits and saves the testing data as a .csv file, 'Saved Data' displays a text remind the user of where to find the collected information, Figure 15b.
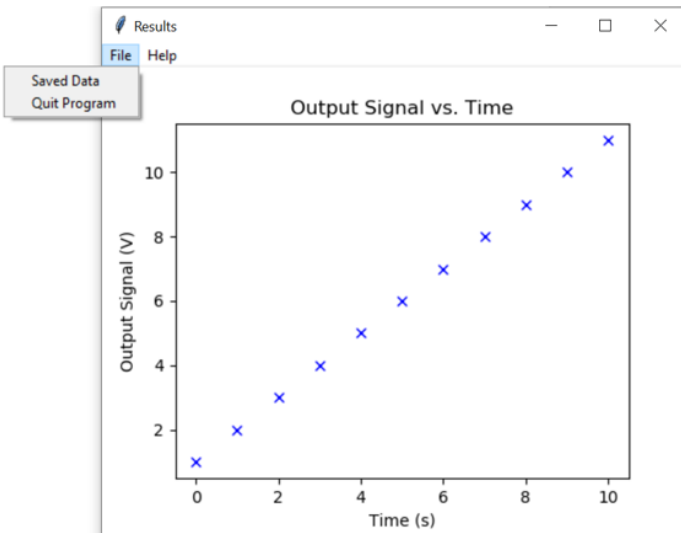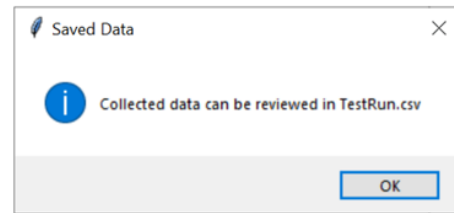
(a)   (b)
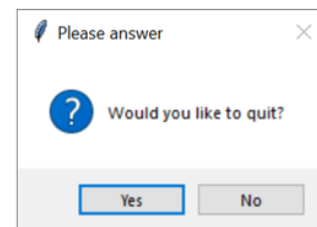
(c)

FIGURE 15: MAIN WINDOW MENU BAR - FILE (GUI)

'Quit Program' does what is expected, it closes the window and its data can be retrieved and replotted by using the program's ability to process .csv information. It displays a question to verify whether the user purposefully clicked the option to terminate the program, Figure 15c. If the user selects 'No,' then they will be returned to the main 'Results' window.

VII. Conclusions

The components can satisfy the previously specified current, frequency, and noise requirements. The prototype board includes a universal ground plane, limiting user and device risks and thus meeting the third engineering specification noted in Chapter II. Its small dimensions fit well within a laboratory test station. Unfortunately, I was not able to create an auto-calibrating system as it falls outside my software knowledge, regardless of my research. It would be a good starting point for a future senior project, building off the presented work within this report.

This circuit and software are optimal for data conversion, processing, and display. Although the product may be useful in some tests, it cannot replace the current test setup for radio-frequency devices, which allows engineers to perform load-pull testing using the same equipment. This project could be effective in other applications, where the main goal relies on signal monitoring rather than running other tests for load matching.

VIII. References

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APPENDIX A – Code

```python
"""
Senior Project Code
@purpose: Current Reading and Plotting in a GUI
@author: Nicolette Ray
@note: using Python 3.7
"""

import tkinter    #version 8.6

import matplotlib
matplotlib.use("TkAgg")
from matplotlib.figure import Figure
from matplotlib.backends.backend_tkagg import FigureCanvasTkAgg

# Useful functions
def check():
    '''Confirm whether user wants to quit program'''
    check_title = 'Please answer'
    check_text = 'Would you like to quit?'
    answer = tkinter.messagebox.askquestion(check_title, check_text)
    if answer == 'yes':
        root.destroy()
    else:  # 'no'
        pass

def reminder():
    '''Remind the user that collected data is available in csv file'''
    reminder_title = 'Saved Data'
    reminder_text = 'Collected data can be reviewed in TestRun.csv'
    tkinter.messagebox.showinfo(reminder_title, reminder_text)

def about_msg():
    '''Message describing the program (purely informational)'''
    about_title = 'About'
    about_text = 'This program graphs output signal vs time to enable faster data analysis. by
Nicolette Ray (2020)'
    tkinter.messagebox.showinfo(about_title, about_text)

def wind_size():
    '''Checking Window Dimensions'''
    wind_width = root.winfo_screenwidth()
    wind_height = root.winfo_screenheight()
    print("Window width:", wind_width)
    print("Window height:", wind_height)

########################################################################
'''
#Collecting data from ADC

#based off of:
# Simple demo of continuous ADC conversion mode for channel 0 of the ADS1x15 ADC.
# Author: Tony DiCola
# License: Public Domain
import time

# Import the ADS1x15 module.
import Adafruit_ADS1x15
# Create an ADS1115 ADC (16-bit) instance.
adc = Adafruit_ADS1x15.ADS1115()

# Note you can change the I2C address from its default (0x48), and/or the I2C
# bus by passing in these optional parameters:
#adc = Adafruit_ADS1x15.ADS1015(address=0x49, busnum=1)

# Choose a gain of 1 for reading voltages from 0 to 4.09V.
# Or pick a different gain to change the range of voltages that are read:
```

```python
#   -  2/3 = +/-6.144V
#   -    1 = +/-4.096V
#   -    2 = +/-2.048V
#   -    4 = +/-1.024V
#   -    8 = +/-0.512V
#   -   16 = +/-0.256V
# See table 3 in the ADS1015/ADS1115 datasheet for more info on gain.
GAIN = 1  #for 1 milliohm Rsense
#GAIN = 4 #for 71.5 milliohm Rsense

# Start continuous ADC conversions on channel 0 using the previously set gain value
adc.start_adc(0, gain=GAIN)
# Once continuous ADC conversions are started you can call get_last_result() to
# retrieve the latest result, or stop_adc() to stop conversions.

timestamp = [] #list of timestamps
adc_val = [] #list of ADC readings

# Read channel 0 for 0.5 seconds
print('Reading ADS1x15 channel 0 for 0.5 seconds...')
start = time.time()
while (time.time() - start) <= 0.5:
    cur_time = time.time()
    timestamp.append(cur_time)
    # Read the last ADC conversion value and print it out.
    value = adc.get_last_result()
    # WARNING! If you try to read any other ADC channel during this continuous
    # conversion (like by calling read_adc again) it will disable the
    # continuous conversion!
    # print('Channel 0: {0}'.format(value))
    adc_val.append(value)
    # Sleep for 0.1 microseconds.
    time.sleep(0.0000001)

# Stop continuous conversion. After this point you can't get data from get_last_result!
adc.stop_adc()

# Adjust timing values with respect to start time
num_times = len(timestamp) - 1
while num_times <= 0:
    timestamp[num_times] -= start
    num_times - 1
'''
########################################################################

# Saving data to a .csv file

# REMOVE ''' TO USE CODE SEGMENT

'''
import csv

amount_data = len(adc_val) - 1

with open('TestRun.csv', 'w', newline='') as csvfile:
    fieldnames = ['time', 'voltage']
    writer = csv.DictWriter(csvfile, fieldnames=fieldnames)
    writer.writeheader()

    while amount_data <= 0:
        writer.writerow({'time': timestamp[amount_data], 'voltage': adc_val[amount_data]})
'''
########################################################################

# If basing the graph from values saved in a .csv file, this code parses through
# it to plot the data
# Reading and plotting data from csv file

# REMOVE ''' TO USE CODE SEGMENT
```

```python
'''
gsplit_data = []
gx_axis = []
gy_axis = []

with open ("TestRun.csv") as myfile:          #replace "....csv" with file name
    lines = myfile.readlines()                 #return a list with each line as an item
    for current_line in lines:
        gsplit_data.append(current_line.split(",")) #split each line at the comma, save as new
list of lists

    for item in gsplit_data:
        if len(item) < 2:    #if the list contains less than 2 items, do nothing
            pass
        else:
            try:
                x = float(item[0].strip()) #convert 1st item to a float & remove spaces
                y = float(item[1].strip()) #convert 2nd item to a float & remove spaces
                #if both actions succeed, append axis lists
                gx_axis.append(x)
                gy_axis.append(y)
            except:
                ValueError #ignore Value errors such as strings not converting
            else:
                #print(gx_axis)
                #print(gy_axis)
                pass
'''
###########################################################################
# GUI Setup
root = tkinter.Tk()
root.geometry("500x400+50+50")
root.title("Results")

figure = Figure(figsize=(5, 4), dpi=100)
plot = figure.add_subplot(1, 1, 1)
plot.set_xlabel('Time (s)')
plot.set_ylabel('Output Signal (V)')
plot.set_title('Output Signal vs. Time')

# IF going from data collected during code run
plot.plot(timestamp, adc_val, color="blue", marker="x", linestyle="")

# IF going from csv file directly
#plot.plot(gx_axis, gy_axis, color="blue", marker="x", linestyle="")

canvas = FigureCanvasTkAgg(figure, root)
canvas.get_tk_widget().grid(row=0, column=0)

# Create Menu Bar
main_menu = tkinter.Menu(root)

# Menu Bar Options
file_menu = tkinter.Menu(main_menu, tearoff = 0)
help_menu = tkinter.Menu(main_menu, tearoff = 0)

# Commands for submenu
file_menu.add_command(label="Saved Data", command=reminder)
file_menu.add_command(label="Quit Program", command=check)
help_menu.add_command(label="About", command=about_msg)

main_menu.add_cascade(label="File", menu=file_menu)
main_menu.add_cascade(label="Help", menu=help_menu)

root.config(menu=main_menu)

# Run GUI
root.mainloop()
```

APPENDIX B — Analysis of Senior Project Design

Project Title: High Speed, High Current Monitoring System

Student's Name: Nicolette Ray

Advisor's Name: Dr. Dennis Derickson

1. Summary of Functional Requirements

The project performs high speed, high current measurements. The software compiles the current data output by a device under testing, generating a graphical representation of output signal vs. time via a graphical user interface, enabling further analysis.

2. Primary Constraints

My limited power transistor testing knowledge makes the visualization of my final product difficult. The learning curve creates obstacles that are surmountable, with time and effort. Chapter II includes a customer needs assessment, creating project timeline restrictions. The sponsor requests faster results than I can produce as they requested a list of required hardware before I began the design process. The input signal's high current and frequency require specific components which can support such levels without deteriorating. Testing the device's compatibility with high currents cannot occur at Cal Poly due to limited equipment. Moreover, the COVID-19 pandemic has limited equipment and lab access.

3. Economic

This project costs significantly less than current products available on the market which consist of automated tuners, various power supplies, and the employee time spent collecting data. Buying initial materials is most costly but they can be bought in bulk. The department can finance portions of the project, but the company sponsor most of the financial support. Real capital consists of tools such as multimeters, scope probes, and wires to test the components. The completion of this project requires many hours of personal work on my end, combined with consulting assistance from industry engineers and meetings with my project advisor. Table 5, Chapter IV, provides an initial and tentative project cost breakdown. The actual project cost breakdown, shown in Table 6 of Chapter IV, includes equipment acquisition which would have been unnecessary under different conditions as I would have had access to these through Cal Poly.

Material	Unit Cost	Quantity	Extended Cost	Justification
Digital multimeter	$32.31	1	$32.31	Prototyping equipment
Soldering iron	$41.97	1	$41.97	
Solder (unleaded) (50 oz)	$4.17	1	$4.17	
Double-sided copper board	$1.30	2	$2.60	
Copper wire (25 ft)	$4.98	1	$4.98	
71.5 mΩ resistor	$0.32	1	$0.32	
1 mΩ resistor	$0.32	1	$0.32	
Intrumentation Amplifier: AD8421A	$6.97	2	$13.96	
Breakout board	$0.50	1	$0.50	
Miscellaneous resistors/capacitors	$0.10	6	$0.60	
ADC: ADS1115	$5.38	1	$5.38	
Raspberry Pi 4	$35	1	$35	Single-board computer
Micro SD card (32 GB)	$10.27	1	$10.27	Raspberry Pi memory
Card Reader	$11.99	1	$11.99	To write to/read the SD card
Micro HDMI to HDMI cable adapter	$6.99	1	$6.99	To connect the Raspberry Pi to a monitor
Total Cost			**$171.36**	

TABLE 6: FINAL BILL OF MATERIALS

The project can hypothetically earn $500 per device, if manufactured commercially. Device users save time by setting up the system to automatically perform measurements rather than manually reconfiguring the testing instruments over the course of several hours. No associated maintenance cost exists unless device power ratings drastically change throughout the years. The development may take up to 6 months, as variations remain unavoidable. After the project ends, the device design is frozen and used to repeatedly manufacture this device.

Chapter IV describes the original project timeline. The Fall 2019 Gantt chart remained accurate. However, my project's objectives were narrowed during Winter 2020 and my advisement changed to Dr. Derickson. This affected productivity. As such, I researched possible current sensors during that time and built a prototype during Spring 2020.

4. **If manufactured on a commercial basis:**

I estimate approximately 110 devices sold per year because few companies dominate the radio-frequency industry and each one only needs ten models due to their project timelines (at least twelve weeks per project means less device testing) [7]. Manufacturing each device costs $100 (based on the cost estimates in Table 5 and manufacturing labor costs). Priced at $500 a unit, sales generate a $44,000 yearly profit. Device operation requires an estimated hour, including set-up.

5. **Environmental**

This project uses electricity and subsequently, the power distribution system. Electricity powers the system's various sub-systems: power supplies, monitor to adjust and display the graphical user-interface (GUI). This project may harm various ecosystems who have settled in areas where nuclear plants exist. Manufacturing the device may also increase air pollution as wires needed to transmit the measured data require conducting and insulating materials. More efficient testing also increases the quantity of devices potentially sold by radio-frequency companies. If it increases product demand, more wafers and, consequently, crystals need creation. This process consumes natural resources and thus impact the environment. This product should maximize the time a person spends signal

monitoring and allow them to spend it on other tasks, thus increasing efficiency and allowing people to focus their energy on saving the environment.

6. Manufacturability

Manufacturing this product may cause difficulties due to component tolerances, slight size variations, and material costs. Incorrect wire connections can lead to skewed measurements or worse, product destruction. Precision makes or breaks the testing device, as the tested components are highly susceptible the electro-static discharge. Material availability is not an anticipated challenge since the project requires pre-made products such as wires, resistors, capacitors.

7. Sustainability

Maintaining the completed device entails staying up to date on device requirements and the required precision of the measured data. If the industry expands and becomes more meticulous, measurements may have a new basis, leading to device modifications. If a user forgets to turn off the device, unnecessary power consumption ensues, thus wasting resources. Remaining mindful of power usage is thus important. The design of this project could be improved by someone who has more experience with pure-software environments, to make the user-interface more organized and accessible. Upgrading the design requires several design iterations as wire and device compatibility, as well as software language updates create various mandatory changes.

8. Ethical

The Golden Rule stating to treat other the way you want to be treated is satisfied by giving credit to the resources that assist me throughout the course of the project development. I also communicate clearly and often with Wolfspeed because I expect the same in return. In accordance with rule 9 of the IEEE Code of Ethics ("to avoid injuring others, their property, reputation, or employment by false or malicious action"), the design of this project must return accurate measurements as customers provide further information to their clients regarding their product's performance by using this testing device [8]. Inaccurate or unreliable data could tarnish the company's reputation and potentially damage their interpersonal connections with other companies.

No conflicts of interest regarding the device design arise since Wolfspeed, company sponsor, reserves the rights to my senior project design. However, I have received an offer letter to work for the company, adding extra pressure to produce a working device. Rule 4 of the IEEE Code of Ethics ("to reject bribery in all its forms") causes risk since the job offer, although technically unrelated to my choice of senior project, could be construed as a form of bribery [8]. By declining the initial offer, the bribery risk no longer exists. I did receive another offer from the company, involving a different group than my point of contact's, eliminating any conflict of interest overlap.

9. Health and Safety

Safety remains inherently important because the device operates using high current levels. A 30 A output current reading can short any device present on the testbench, if improperly grounded. To avoid such mishaps, the user performs measurements on a grounded platform. The tested devices are susceptible to electro-static discharge (ESD), precautions must be taken when manipulating such parts.

10. Social and Political

The project's direct stakeholders include the sponsor, Cal Poly, and me. Wolfspeed wants to increase their efficiency when testing power transistors through this new device. Cal Poly needs this report and others like it to renew their ABET accreditation while I need this project so I can graduate this spring. The project creates inequities because the different parties involved have varying expectations and ideal timelines. The company's expectations

require an initial design prototype bill of materials in December 2019, while Cal Poly expects it partway through February 2020. Having a company sponsor creates additional pressure to produce valuable results as they have influence within the RF industry, impacting the relevance of my final project.

11. Development

Having no experienced with noise analysis, I became well-versed with the practice through readings and LTSpice simulations. Prototyping under restricted conditions taught me dead-bug construction using Manhattan-style and enhanced my surface-mount device soldering skills. I improved my project management and planning skills, ensuring the project's success. The literature search included below and in Chapter VII contributed important clarifying information. Market research and a better product cycle understanding have emerged throughout the project course.

[1] Wolfspeed, "Thermally-Enhanced High Power RF GaN on SiC HEMT 400 W, 48 V, 3600 – 3800 MHz," GTRA384802FC datasheet, 2 July 2019.

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